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SCIENCE SERVICES DIVISION

TEXAS INSTRUMENTS
INCORPORATED

ADVANCED ARRAY RESEARCH

Quarterly Report No. 3

15 June 1967 through 14 September 1967

George Hair, Program Manager
Area Code 214, 238-3473

TEXAS INSTRUMENTS INCORPORATED
Science Services Division
P.O. Box 5621
Dallas, Texas 75222

Contract No. F33657-67-C-0708-P001
Beginning 15 December 1966
Ending 14 December 1967

Prepared for

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Washington, D.C. 20333

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ARPA Order No. 624
AFTAC Project No. VT/7701

6 October 1967

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TEXAS INSTRUMENTS

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SCIENCE SERVICES DIVISION

6 October 1967

Air Force Technical Applications Center
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Headquarters, USAF
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Alexandria, Virginia 22314

Attention: Captain Carroll F. Lam

Subject: Quarterly Report No. 3 for period 15 June 1967 through 14 September 1967

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WORK PROGRESS

Progress during the third quarter is presented in this report by principal tasks. Areas of current investigation and plans for the fourth quarter are also presented.

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Task A

Using an ensemble of seismic array network data to be furnished by AFTAC, investigate bodywave noise on a coherent worldwide basis. Investigate interarray equalization problems. Study methods of combining the subarray output for network signal extraction. Investigate the capabilities of a worldwide network for resolving events closely spaced in time and space.

Using data from the CPO array, several procedures for computing f-$\vec{k}$ spectra have been compared in order to choose an optimum technique for the study of bodywave noise at the station level. Conventional and high-resolution techniques were compared using conventional correlation-transform techniques and also using the direct transform (Cooley-Tukey) method. Consistent results were obtained for all cases. The direct transform, high-resolution procedure was determined optimum from the standpoint of spatial definition and computation time.

Further comparisons were made to explore normalization procedures, optimum signal-to-noise ratio and the extent of variation in spectral estimate due to the choice of reference sensor. In terms of spatial stability and relative insensitivity to both reference sensor choice and signal-to-noise ratio, f-$\vec{k}$ spectra computed from unsmoothed direct transforms proved superior to those computed from smoothed transforms. An additional advantage is the applicability of a computational shortcut significantly reducing required computation time. With this method, an f-$\vec{k}$ spectrum may be computed representing the average of the individual spectra computed for each reference sensor in approximately the time formerly required to obtain each individual spectra. A description of this method will be included in Special Report No. 6,* now being prepared.

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*Texas Instruments Incorporated, 1967: Advanced Array Research Spec. Rpt. No. 6, Contract No. F33657-67-C-0708-P001, to be published.

Using high-resolution f-$\vec{k}$ spectra, a study of the bodywave noise observed at the station level has been proceeding. All array stations were examined using two noise samples chosen for analysis from meteorological data indicating large storm centers. Ten frequencies were examined from 0.2 Hz to 2.0 Hz in 0.2 Hz increments. Unsmoothed direct transforms were computed over a 410-sec data gate, and high-resolution f-$\vec{k}$ spectra were computed from these transforms. The results of this analysis will be reported in Special Report No. 6. This report will also summarize station array characteristics, such as location, configuration and straight sum responses. A description of the two noise samples used will be included along with available meteorological data.

A technique for obtaining worldwide f-$\vec{k}$ spectra, using network station outputs as components of a worldwide array, has been programmed and is being evaluated using synthetic data. The procedure is essentially a beam-steer in the frequency domain and is designed for detection of bodywave energy. The procedure will be used subsequently for extraction of high-velocity noise and signals at the network level. A special report will be prepared describing the technique and the results of the evaluation.

The comparison of techniques for removal of low-velocity energy at the station level is proceeding. Conventional disk model MCF's, both from measured and theoretical designs, straight-sum and beam-steer outputs, and maximum-likelihood adaptive procedures are being compared. Initial results indicate that the maximum-likelihood adaptive procedure will probably not be satisfactory for medium-to-high velocity noise extraction. Disk-model adaptive procedures would be preferable but are not routinely operational at this time.

An initial study has been made of signal similarity across the network. Earthquake data was utilized due to an unanticipated delay in receipt of explosion recordings. Correlation coefficients have been computed and analyzed to determine which station appears most representative of the network, i.e., to which station the network should be equalized.

Significant equalization problems are observed, and a theoretical investigation of different methods to minimize the mean-square-error on a network basis is underway. Specifically, a method that does not require the choice of a target or reference station is being examined.

Processing of a second event, Kurile 2, under the worldwide signal extraction study is nearing completion. For this study, various processing techniques are examined in order to determine the optimum technique to enhance teleseismic signals at the network level. Techniques examined include simple beam-steer, weighted beam-steer, and the beam-steer of Levinson equalized data. Both unprocessed and bandpassed data are used.

Different types of weighting, including signal-to-noise ratios, signal ratios and noise ratios, have been analyzed in the weighted beam-steer technique. Results of this study indicate that the optimum technique is a combination of signal-to-noise ratio weightings and Levinson equalization of bandpassed data. However, due to the additional processing costs of the technique, several additional tests will be performed to determine if the use of Levinson equalization filters is warranted. Levinson filters studied thus far have been designed for and applied to the same event; on-line processing will require the development of a set of filters for each signal area of interest. The use of filters designed from an ensemble of events will be evaluated when additional events have been processed and analyzed.

The phase-extraction study has been limited by the lack of available events containing good depth phases. However, the second event processed for the signal extraction study does contain several later arriving

phases. The two analyzed events will be studied using P-30 correlation, square-and-integration of P-30 correlations, and a time shift of the P-30 correlations using time shifts based upon pP-P time differences to enhance depth phases.

A special report on the signal extraction and phase extraction studies is being prepared for publication during the coming quarter.*

Task B

Continue investigations of multi-element system studies to determine possible new combinations of sensors for noise reduction. Study methods of specifying, for given noise fields, the optimum multisensor system for noise reduction with the desired result a set of guidelines for array design. These guidelines should include, but not be limited to, the type of sensors required and, for an array, the size and geometry, subject to the constraints of practicability.

1. Program for Computing Theoretical Crosspower Spectra and/or Crosscorrelation Functions

The following is a resume of the work done toward developing the crosspower/crosscorrelation matrix program and the reason for this work.

The need for this program arises in two areas of our work. In attempting to assess the potential value of arrays which employ new geometries and/or various types of instruments, it is often desirable

*Texas Instruments Incorporated, 1967: Advanced Array Research Spec. Rpt. No. 7, Contract No. F33657-67-C-0708-P001, to be published.

to begin with a theoretical study of processors for the arrays. To do this, it is necessary to specify representative signal and noise fields and then to obtain the resultant crosspowers between various elements of the array. This type of analysis has been done for horizontal-vertical seismometer arrays and for vertical arrays. It is possible that additional vertical array work of this nature may be warranted.

The second need arises in designing filters. In designing filters for application to data from an existing array, it is necessary to obtain the signal and noise crosscorrelation matrices. While use of measured noise is customary for this purpose, it is generally difficult to obtain signal records of sufficient quality and duration to provide an adequate statistical representation of the signal. The best solution is often to generate the signal statistics theoretically.

The program now being developed would be a substantial improvement over previous programs which provide this type of information. Programs currently available handle separate parts of the overall problem. By properly employing a series of these programs, it is possible to obtain the desired result. In practice, however, as a result of the complexity of this approach and unfamiliarity with the programs, the goal is either achieved at undue expense or an inferior result is accepted. The new program would treat the entire problem and in such a way as to make it readily accessible to potential users.

Programs now available are not adequate for all situations. For example, theoretical work on horizontal seismometers necessitated writing a new program. The approach was such that the program does not output the crosspower matrices for such arrays and thus, we do not currently have this capability. New situations of immediate interest can be treated by the new program and, more importantly, the new program will be readily extendable to other configurations as they arise.

The first case considered during the development of this program was the relatively simple case involving a surface array of vertical seismometers and the solid disk f-$\vec{k}$ space model. Mathematical representation of the solid disk f-$\vec{k}$ is as follows:

$$P(f, \vec{k}, \theta) = \frac{v^2}{\pi f^2} \qquad \text{for} \quad 0 \le \vec{k} \le \frac{f}{v} \;, \quad 0 \le \theta \le 2\pi$$

In this case, where v is the minimum apparent velocity for the model, it is not necessary to consider the crustal structure of the medium. In effect, whatever the crustal structure, excitation will be assumed such that the resultant vertical motion at the surface is described by this f-$\vec{k}$ space model. It is a simple matter to compute the resulting crosspower spectra. Flexibility is achieved by combining two such models to form an annulus and by tilting the model to simulate anisotropic propagation.

Obtaining crosspower spectra for arrays involving vertical and horizontal seismometers using the mode for vertical motion was the next step attempted. In this case, it was necessary to consider the crustal structure, since this determines the relationship between horizontal and vertical motion. The most simple structure is the infinite halfspace. Even in this simple case, the model given above was not tractable. It was replaced, therefore, by the following models, one for isotropic and the other for directional propagation.

$$P_I(f, \vec{k}, \theta) = \frac{1}{2\pi \vec{k}} \quad \delta(\vec{k} - \frac{f}{v}) \quad \text{for} \quad 0 < \theta < 2\pi$$

$$P_D(f, \vec{k}, \theta) = \frac{1}{\vec{k}} \quad \delta(\vec{k} - \frac{f}{v}) \;\; \delta(\theta - \theta_1)$$

In these models, the symbol δ represents the delta function. This is not a serious limitation, since any continuous model can be simulated as closely as possible by combining groups of such models with appropriate values of v and θ. A more serious objection is the fact that the case involving horizontal-vertical seismometer arrays requires slightly different treatment than does the case involving all vertical seismometer arrays. This difficulty would be compounded as further extensions, such as multilayer crustal structures, vertical arrays and dispersive propagation, are contemplated. By starting from a special case and attempting to go to the general case, the unity of the problem was being obscured, making it obvious that a new approach was needed.

The key to this problem is to treat the multilayer crustal structure immediately. By employing the Haskell matrix formation, it is a straightforward matter to obtain f-$\vec{k}$ space transfer functions between any combinations of vertical and horizontal seismometers at different depths. Moreover, these relationships are of the same basic form for both bodywave and dispersive propagation. These transfer functions and the second two f-$\vec{k}$ space models given above are all that is required to calculate the desired crosspower spectra. Love waves require a slight modification due to the absence of vertical motion, but the same general treatment can be applied.

Use of this approach provides the unified theory necessary for implementation of the program. The remaining task is to actually do the programing.

We believe that the program can be completed to treat arrays of vertical and horizontal inertial seismometers within the duration of the present contract. This will require about three man-months and seven hours of computer time.

2. Analysis of the WMO Noise Sample

Three noise samples recorded at WMO in 1962 have been analyzed using $\vec{k}$-line wavenumber spectra. The most interesting result of this study is the identification of broadband Rayleigh-wave energy (0.2 to 1.0 Hz) coming from the northeast. The broadband character of this energy indicates a source relatively close to the array. Two small lakes located northeast of the array appear to be likely sources. It was also possible to obtain some information about the 2 Hz noise characteristics of this site. This 2 Hz energy was found to be propagating in one of three directions. Choice of one of these three directions is prevented by the aliasing properties of the array configuration. Velocities associated with each of the three possible directions are all close to 3 km/sec. The high degree of repeatability between the three samples indicated that, subject to this ambiguity, the source direction is known rather precisely. Details of this analysis are presented in Special Report No. 2.*

3. Data Recording at the WMO Horizontal Seismometer Array

Data are currently being digitally recorded from the array of horizontal seismometers at WMO. These data will be used to experimentally study the proposition that teleseismic signal enhancement can be accomplished by using the horizontal seismometer outputs to predict the surface wave noise on a central vertical seismometer. The data will be processed using both conventional MCF design and adaptive filter design techniques. Data from the shallow-buried array of vertical seismometers is also being recorded for possible use in

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*Texas Instruments Incorporated, 1967: Analysis of K-Line Wavenumber Spectra from Three WMO Noise Samples, Advanced Array Research Spec. Rpt. No. 2, Contract No. F33657-67-C-0708-P001, 30 Sept.

interpreting the results. In addition, the strain seismometer outputs are being recorded for possible future use. Because of the nature of the array, a possible additional benefit of this recording effort may be resolution of the ambiguity in the direction of propagation of the 2 Hz noise.

Tasks C and D

> Theoretically investigate methods of implementing continuously adaptive systems for application to time-varying noise fields and postdetection processing. Any system that can be simulated off-line should be evaluated using suitably characteristic data. Investigate the effects and methods of reducing locally generated noise. The effects of such non-plane wave fields on multichannel filter design should be evaluated.

Work during the third quarter consisted of

- Prediction error processing of additional data samples
- Development of an adaptive filtering program for signal extractions based on a theoretical signal model
- Implementation of a second maximum-likelihood algorithm

At the beginning of the third quarter, adaptive prediction error filtering had been completed on four data samples. These were short-period vertical data from surface arrays. In order to establish a broader base for study of adaptive techniques, adaptive prediction error filtering was undertaken on eight additional data samples. These samples included data from an array of long-period 3-component instruments, deep-well vertical array

data, and ring stacked short-period vertical data, as well as the usual short-period vertical surface array data. All data samples except the vertical array data were processed both before and after prewhitening. Plots of mean-square-error vs k_s (the rate of convergence parameter) mean-square-error vs time, power spectra, and false alarm probability are used in comparing the adaptive results with Wiener results from the same data. The most apparent observations from the results are

- Adaptive filter outputs approach Wiener results as k_s approaches zero for both whitened and nonwhitened data
- Mean-square-error increases rapidly with increasing k_s in every case for whitened data, while for nonwhitened data mean-square-error decreases slightly with increasing k_s for some of the data samples

A computer program for adaptive signal extraction based on a theoretical signal model was completed during the third quarter. Check-out on this program is in progress. Tests on the running time of this program indicate that this type of processing will be economically competitive with Wiener signal extraction if the number of channels is less than ten and the number of filter points less than twenty-five.

In Special Report No. 1* it was shown that maximum-likelihood filtering could be reduced to a problem of predicting one channel of the data from the other channels minus the channel to be predicted. During the past quarter an additional maximum-likelihood algorithm has been programed

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*Texas Instruments Incorporated, 1967: Adaptive Filtering of Seismic Array Data, Advanced Array Research Spec. Rpt. No. 1. Contract No. F33657-67-C-0708-P001, 18 Sept.

where the mean across channels is predicted from the set of channels formed by subtracting the mean from each channel. To date, two samples have been processed by both of these maximum-likelihood algorithms for the purpose of comparing the methods. Results indicate that in terms of mean-square-error the two processes are similar. However, the frequency content of the output traces appears to be different for each type of filtering. Investigation into the reasons for this difference is planned for the coming quarter.

Task E

> Continue studies of the instrumental equalization problem. Apply any new techniques available for studying instrumental equalization and evaluate the effectiveness of such techniques.

1. Statistical Misdesign Study

Special Report No. 3* contains the derivation and probability curves for the statistical design parameters α and β under the Gaussian assumption. (α is the ratio of the true mean-square-error of the measured filter to the mean-square-error, and β is the ratio of the measured mean-square-error of the measured filter to the minimum mean-square-error.) These curves should be used in all future experimental planning. Special Report No. 5** contains generalization of the scalar α and β quantities into α and β matrices. This latter work, although directed toward practical problems, has no apparent application at present. Special Report No. 5 does contain a possibly more enlightening discussion of the derivation of α and β than contained in Report No. 3.

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*Texas Instruments Incorporated, 1967: Statistics Governing the Design and Performance of Noise-Prediction Filters, Advanced Array Research Spec. Rpt. No. 3, Contract No. F33657-67-C-0708-P001, 8 Sept.

**Texas Instruments Incorporated, 1967: Advanced Array Research Spec. Rpt. 5, Contract No. F33657-67-C-0708-P001, to be published.

2. Long-Noise Sample Study

Preparations for analyzing a very long-noise sample from LASA are being discontinued because of lack of sufficient funds to perform the work adequately.

Obtaining a suitable LASA long-noise sample does not appear to be a major problem. DAC playouts, supplied to us by SDL, of LASA subarray data recorded on 5 December 1966 and 12 December 1966 indicate that at any time one can expect to find several subarrays which are fully operating with a minimum of locally generated noise. By ignoring weak teleseisms, which would contribute almost no energy to the total recording, 10 hour and longer noise periods are readily uncovered. There are some recording error problems, such as channel dropouts in the multiplexing and zeroing of data, but these errors seem amendable to automatic detection and correction.

A primary analysis technique currently being used to study LASA noise is the measurement of group coherence. The application of this analysis technique to the TFO long-noise sample and the design and interpretation of group coherence multichannel filters in terms of equalization problems will constitute the primary effort under Task E during the next quarter.

FINANCIAL STATUS

The financial status of the project as of 31 August 1967 is summarized on the Cost Planning and Appraisal Chart submitted under separate cover.

No significant total variance from the original cost estimate is anticipated.

Very truly yours,

TEXAS INSTRUMENT INCORPORATED

George Hair

George Hair
Program Manager

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13. ABSTRACT

Progress during the third quarter, present effort and plans for future work in the areas of network studies, multisensor arrays, continuously adaptive filtering, near-array noise sources, and intra-array equalization studies are presented.

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